

# Intermediate mass dileptons from the passage of jets and high energy photons through quark-gluon plasma

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The production of the intermediate mass dileptons originating from the annihilation and Compton scattering of the jets and high energy photons (resolved photons) passing through the quark-gluon plasma is calculated. The contribution of the dilepton yield due to the jet-plasma and high energy photon-plasma interaction is pronounced compared to the thermal and Drell-Yan dilepton spectrum at intermediate mass. The ordinary spectrum of thermal and Drell-Yan processes is enhanced by the jet and photon-plasma mechanism. The numerical results match to the PHENIX data accurately in the intermediate mass region for Au-Au 200 GeV/A collisions at RHIC.

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The most important goal in the study of relativistic heavy ion collisions is to probe the exact information of the quark-gluon plasma (QGP). Since dileptons do not interact strongly, it is relatively easy to probe the thermal dilepton information emitted from the hot QGP in the short creating and cooling time [1–12]. However, so far no evident experiments show that some information are exactly produced from the QGP. For the theory of the phase transition, thermal dileptons are dominant in the intermediate mass region between the  $\phi$  and the  $J/\Psi$  vector meson, but the contribution of dileptons in this mass region also can be explained by the decays of charmed mesons [13–17].

Recently, the measurement of the dilepton continuum at Relativistic Heavy Ion Collider (RHIC) energies was performed by the PHENIX experiments for Au-Au 200 GeV/A collisions [18]. The dilepton yield in the low mass range between 0.2 and 0.8 GeV is enhanced by a factor of 2~3 compared to the expectation from hadron decays. In fact, such phenomena were found at Super Proton Synchrotron (SPS), the enhancement of the dilepton yield at SPS was successfully interpreted by the models of the mass dropping or melting in a hot medium due to the chiral symmetry restoration, but such modifying scenarios can not well explain the enhancement in Au-Au collisions at RHIC [19–27]. The imperfect modifying models of hadron decays present other probable mechanisms to explain the enhancement of the dilepton yield at low mass. Moreover, the dilepton enhancement at RHIC is implied that such phenomena are related strongly to the hot plasma scenario.

The contribution of thermal dileptons at the low mass is covered by the cocktail of hadron decays due to the vector meson peaks is more pronounced than the thermal spectrum. Then the thermal information is only evident in the intermediate mass region. The dileptons produced from jet-plasma and photon-plasma interactions contain a thermal information coming from the quark-gluon plasma. Therefore the dileptons produced from the passage of large transverse momentum ( $P_T$ ) jets and photons passing through the hot medium are also pronounced at intermediate mass. The dileptons produced in the large  $P_T$  jet-plasma and  $\gamma$ -plasma inelastic scatterings turns into an important dilepton production source at intermediate mass. This jet and photon-plasma conversion is absent in  $p-p$  collisions.

The jet-dilepton conversion mechanism was discussed by Srivastava before [28, 29]. However, it is the first time to rigorously discuss the jet-dilepton and photon-dilepton conversions for the hot medium system in this Letter.

In pQCD the transverse momentum of photons can arise by the hard bremsstrahlung of high energy gluons which can be calculated perturbatively if the momentum transfers are large. The perturbative component of the large  $P_T$  photons is generated by the following subprocess:  $q\bar{q} \rightarrow g\gamma$ ,  $qg \rightarrow q\gamma$  and  $q\bar{q} \rightarrow (q \rightarrow q\gamma)q$  [12, 30, 31]. The idea of  $\gamma$ -plasma interaction is based on the QED Compton cross section:  $q_{th}\gamma \rightarrow q_{th}(\gamma^* \rightarrow l\bar{l})$  when a high energy photon passing through the quark-gluon plasma, where  $q_{th}$  denote the thermal partons in the hot plasma.

Furthermore the dilepton production associated with resolved photon-plasma interaction is also discussed. Heisenberg uncertainty principle allow a photon for a short time also to fluctuate into a quark-antiquark pair. Therefore a high energy photon looks like surrounded by a quark cloud, and can be interpreted that it has a inner parton structure [32]. When the photons emitted by the hard collisions have large transverse momentum, the photons which include inner parton structure are hadron-like, so a target thermal parton in the medium reacts with the photon-parton in the processes of  $q_\gamma\bar{q}_{th} \rightarrow \gamma^* \rightarrow l\bar{l}$ ,  $q_\gamma\bar{q}_{th} \rightarrow g(\gamma^* \rightarrow l\bar{l})$ ,  $q_\gamma g_{th} \rightarrow q(\gamma^* \rightarrow l\bar{l})$  and  $(q_{th}g_\gamma \rightarrow q\gamma^*)$ , where the photon-parton  $q_\gamma/\bar{q}_\gamma$  and  $g_\gamma$  depends on the large  $P_T$  carried by the high energy photons.

In this paper, we rigorously derive the dileptons production rate of the high energy jet-dilepton and photon-dilepton conversion. Let us start with considering the yield of dileptons in the jet-plasma and photon (resolved photon)-plasma interactions. Using kinetic theory of the two body interaction  $p_1 p_{2(th)} \rightarrow p_{3(l\bar{l})} p_4$ , the production rate

is  $R_{l\bar{l}} \propto \int d^3\tilde{p}_1 \int d^3\tilde{p}_2 f(p_1)f(p_2)v_{12}\sigma$ , where  $d^3\tilde{p} = d^3p/(2\pi)^3$  and the relative velocity is  $v_{12} = (p_1 + p_2)^2/2p_1^0p_2^0$ . In the limit  $P_T^{l\bar{l}} \rightarrow 0$  the momentum integration finally can be written into a one dimension form

$$\frac{dR_{l\bar{l}}}{dM^2} = \frac{6}{(2\pi)^4} \int dP_T f_{jet/q_\gamma}(P_T) T M^2 e^{-\frac{M^2}{4P_T T}} \sigma_{DY}, \quad (1)$$

where  $f_{jet/q_\gamma}$  is the distribution of large  $P_T$  jets and the distribution of partons in a high energy photon, respectively. Note that the gluon jets and real photons will contribute only at high order. Here  $\sigma_{DY} = K \frac{4\pi\alpha^2 e_q^2}{9M^2}$  is the standard cross section of Drell-Yan process with a  $K$  factor  $K = 1 + 2.09\alpha_s$ . If the distribution is replaced by the thermal Boltzmann distribution  $e^{-P_T \cosh y/T}$ , one can derive the standard rate of the thermal dileptons production as [1]  $dR_{l\bar{l}}/dM^2 = \frac{6\sigma_{DY}}{(2\pi)^4} M^3 T K_1(\frac{M}{T})$ .

The phase-space distribution of jets and high energy photons (resolved photons) is as follows

$$f_{jet/q_\gamma}(p) = \frac{2(2\pi)^3}{g_{q/\gamma} V_{ch} P_T \cosh y} \frac{dN_{jet/q_\gamma}}{d^2 P_T dy} \delta(\eta - y), \quad (2)$$

where  $g_{q/\gamma}$  is the spin(polarization) and color degeneracy of a quark and a photon, respectively. Here  $g_q = 6$  and  $g_\gamma = 2$ .  $\eta$  is the space-time rapidity of the hot system.  $V_{ch}$  is the system volume. One can treat the production rate of the jets and photons by scaling the results for the cross section of Nucleon-Nucleon collisions with the nuclear thickness for a head-on collision in the form  $dN/d^2 P_T dy = T_{AA} d\sigma/d^2 P_T dy$ , where the nuclear thickness for zero impact parameter is  $9A^2/8\pi R_\perp^2$ ,  $R_\perp$  is the radius of the fireball. we take the initial radius of the QGP as  $R_\perp = 4 \sim 8$  fm for RHIC Au-Au  $\sqrt{S_{NN}}=200$  GeV collisions [29].

We choose the accelerating expanding volume of the cylindrical hydro-type as  $V_{ch}(\tau) = 2(z_0 + v_z \tau + \frac{1}{2} a_z \tau^2) \pi (R_0 + \frac{1}{2} a_\perp \tau^2)^2$  [3]. The value of  $z_0$  equals to the QGP formation time  $\tau_0$ . After expanding the terms of  $V_{ch}(\tau)$ , a simple form of the system volume can be deduced as  $V_{ch}(\tau) = V_0 + \sigma \tau + a_V \tau^2 + \mathcal{O}(\tau^3, \tau^4, \tau^5, \tau^6)$ , where the parameters  $V_0 = 2\pi R_0^2 z_0$ ,  $\sigma = 2\pi v_z R_0^2$  and  $a_V = \pi R_0^2 a_z + 2\pi R_0 z_0 a_\perp$ . The authors in Ref. [1] take the value of the transverse area as  $\sigma \sim 100 \text{ fm}^2$  for  $T_0 \sim 200\text{-}300$  MeV. If we choose the radius of the transverse area as  $R_{QGP} \sim 4$  fm, one can immediately find that the longitudinal velocity  $|v_z| \sim 1$ . The values of the parameters  $a_z$  and  $a_\perp$  in the accelerating terms are relatively smaller than the value of  $v_z$ , which means that the term  $\mathcal{O}(\tau^3, \tau^4, \tau^5, \tau^6)$  is negligible. These accelerations are adjusted to the final conditions of flow velocities.

We now turn our attention to the production rate of the jets and photons. The cross section of high energy jets ( $qq \rightarrow qq$ ,  $qg \rightarrow qg$ ,  $q\bar{q} \rightarrow gg$ ,  $gg \rightarrow q\bar{q}$  and  $gg \rightarrow gg$ ) is given by [31]

$$\begin{aligned} \frac{d\sigma_{jet}}{d^2 P_T dy} &= \int_{x_a^{min}}^1 dx_a G_{A/a}(x_a, Q^2) G_{B/b}(x_b, Q^2) \\ &\times \frac{x_a x_b}{x_a - x_1} \frac{1}{\pi} \frac{d\hat{\sigma}_{ab \rightarrow jet}}{d\hat{t}}, \end{aligned} \quad (3)$$

we choose the parton distribution  $G_{N/n}(x, Q^2)$  of the nucleon from GRV [30] in the form  $G_{N/n}(x, Q^2) = R(x, Q^2, A)[ZP(x, Q^2) + (A - Z)N(x, Q^2)]/A$ , where  $R(x, Q^2, A)$  is the nuclear shadowing factor [33],  $Z$  is the proton number of the nucleus and  $A$  is the nucleon number.  $P(x, Q^2)$  is the proton distribution, and  $N(x, Q^2)$  is the neutron distribution. Since protons and neutrons have different distribution of up and down valence quarks, the effect of the iso-spin can be represented by the sum of the proton and neutron distribution. The treatment that without the shadowing and iso-spin effect will overestimate the dilepton contribution in the high  $P_T$  region [27]. The best scale of the transverse momentum is  $Q^2 = p_{a,bT}^2 = 4P_T^2$  in the  $Q^2$  dependent QCD structure functions  $G_{N/n}(x, Q^2)$ . One can find the photon-parton distribution function from M. Glück et al. We have taken the  $Q_\gamma^2 = q_T^2 = p_{a,bT}^2$  [30].

The large  $P_T$  photons emitted by the subprocesses  $q\bar{q} \rightarrow g\gamma$  (ann.) and  $qg \rightarrow q\gamma$  (Com.) in the heavy ion collisions satisfy the cross section ( $A + B \rightarrow \gamma + X$ ) in the following [12]

$$\begin{aligned} \frac{d\sigma_{dir.-\gamma}}{d^2 P_T dy} &= \int_{x_a^{min}}^1 dx_a G_{A/a}(x_a, Q^2) G_{B/b}(x_b, Q^2) \\ &\times \frac{x_a x_b}{x_a - x_1} \frac{1}{\pi} \frac{d\hat{\sigma}_{Com.,ann.}}{d\hat{t}}, \end{aligned} \quad (4)$$

where the minimum volume of the momentum fraction are  $x_a^{min} = x_1/(1 - x_2)$ , and the fraction of nucleon  $B$  is  $x_b = x_a x_2/(x_a - x_1)$ , here  $x_1 = \frac{P_T}{\sqrt{S_{NN}}} e^y$ ,  $x_2 = \frac{P_T}{\sqrt{S_{NN}}} e^{-y}$ .

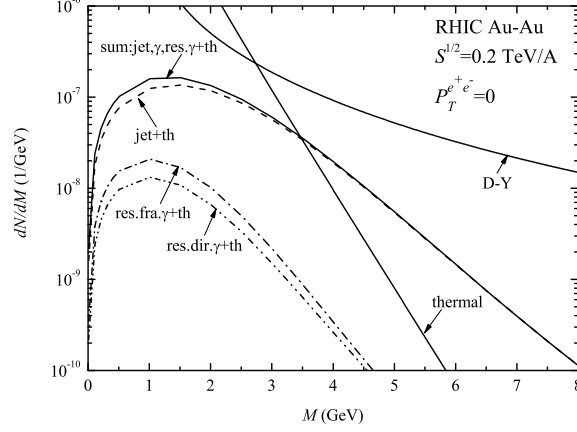


FIG. 1: The dileptons produced from jet-plasma and  $\gamma$ (res.  $\gamma$ )-plasma interactions at RHIC for Au-Au  $\sqrt{s_{NN}}=200$  GeV collisions. The contribution of the  $\gamma$ -dilepton conversion is included into the  $K$  factor of the jet-dilepton conversions.

The cross section of photon fragmentation processes  $qq \rightarrow (q \rightarrow q\gamma)q$  is given by the following [12]

$$\begin{aligned} \frac{d\sigma_{fra.-\gamma}}{d^2P_T dy} &= \int_{x_a^{min}}^1 dx_a \int_{x_b^{min}}^1 dx_b G_{A/a}(x_a, Q^2) \\ &\quad \times G_{B/b}(x_b, Q^2) D_q^\gamma(z, Q^2) \\ &\quad \times \frac{1}{z\pi} \frac{d\hat{\sigma}_{qq \rightarrow qq}}{d\hat{t}}, \end{aligned} \quad (5)$$

where  $D_q^\gamma(z, Q^2)$  is the photon fragmentation function. The minimum volume of the fraction for parton  $b$  is  $x_b^{min} = x_a x_2 / (x_a - x_1)$ , and the fraction  $z = x_1/x_a + x_2/x_b$ . One can see the cross sections for the subprocesses of  $q\bar{q} \rightarrow g\gamma$ ,  $qg \rightarrow q\gamma$  and  $qq \rightarrow qq$  in the Ref. [31].

The yield of photon-partons relevant to the Compton, annihilation and fragmentation processes are derived in the following

$$\begin{aligned} \frac{d\sigma_{res.dir.-\gamma}}{d^2P_T dy} &= \int_{x_a^{min}}^1 dx_a \int_{x_b^{min}}^1 dx_b G_{A/a}(x_a, Q^2) \\ &\quad \times G_{B/b}(x_b, Q^2) G_{\gamma/q_\gamma(g_\gamma)}(z, Q_\gamma^2) \\ &\quad \times \frac{1}{z\pi} \frac{d\hat{\sigma}_{Com.,ann.}}{d\hat{t}}, \end{aligned} \quad (6)$$

and

$$\begin{aligned} \frac{d\sigma_{res.fra.-\gamma}}{d^2P_T dy} &= \int_{x_a^{min}}^1 dx_a \int_{x_b^{min}}^1 dx_b \int_{z_1^{min}}^1 dz_1 \\ &\quad \times G_{A/a}(x_a, Q^2) G_{B/b}(x_b, Q^2) \\ &\quad \times D_q^\gamma(z_1, Q^2) G_{\gamma/q_\gamma(g_\gamma)}(z_2, Q_\gamma^2) \\ &\quad \times \frac{1}{z_1^2 z_2 \pi} \frac{d\hat{\sigma}_{qq \rightarrow qq}}{d\hat{t}}, \end{aligned} \quad (7)$$

where  $G_{\gamma/q_\gamma(g_\gamma)}(z, Q_\gamma^2)$  is the parton distribution of the resolved photons, here  $z_1^{min} = x_1/x_a + x_2/x_b$  and  $z_2 = x_1/z_1 x_a + x_2/z_1 x_b$ .

Since direct real photons are produced directly from the two body kinetic reactions  $qg \rightarrow q\gamma$  and  $q\bar{q} \rightarrow \gamma g$ . The transverse momentum of direct real photons can arise by the direct hard bremsstrahlung of high energy gluons. The

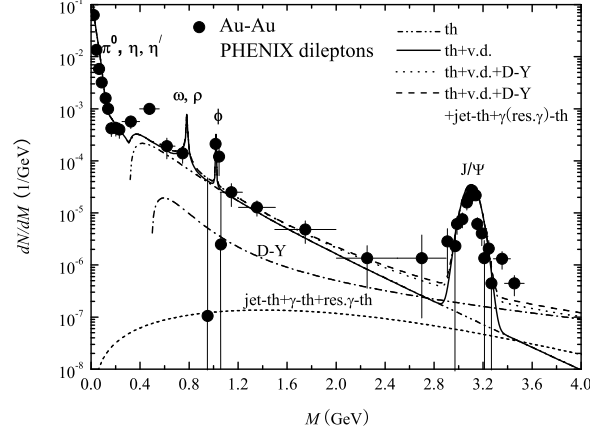


FIG. 2: The dileptons produced from jet-plasma and  $\gamma(\text{res. } \gamma)$ -plasma interactions with PHENIX data for Au-Au  $\sqrt{s_{NN}}=200$  GeV collisions at intermediate mass. Data from Ref. [18].

large  $P_T$  carried by the real photons depends on the cross sections of  $ab \rightarrow c\gamma$  and  $ab \rightarrow c(d \rightarrow d\gamma)$  subprocesses. However, the yield of real photon-plasma may be depressed by the mean cross sections  $\sigma(q_{th}\gamma \rightarrow q\gamma^*)$  due to the lower coupling parameter  $\alpha^3$ . In the integration of mean cross section  $\sigma = \int \frac{d\sigma}{dt}(P_T)dt$ , a divergence exists since the Mandelstam term  $1/\hat{t}$  in the cross section is divergent in the limit  $\hat{t} \rightarrow 0$ . After the virtual gluon regularization [12], a finite results can be expressed as  $\sigma(q_{th}\gamma \rightarrow q\bar{l}\bar{l}) = \frac{\alpha}{\pi}\sigma_{DY}$  which can be contained into the  $K$  factor of the jet-plasma processes. In the hot medium the traditional yield of the Drell-Yan process  $q_{th}\bar{q}_{th} \rightarrow \gamma^* \rightarrow l\bar{l}$  does not include the Mandelstam terms of  $1/\hat{t}$ , the processes will not diverge in the infrared limit  $P_T^{e^+e^-} \rightarrow 0$ . In fact, the energy spectrum of Drell-Yan process is longitudinal, namely  $E_{\gamma^*}^2 = P_L^2 + M^2$ , where  $P_L$  is the longitudinal momentum of dileptons.

In Fig. 1 we plot the contributions for jet-dilepton and resolved photon-dilepton conversion without the vacuum vector meson decays. The value of the jets distribution  $f_{jet}(p)$  is larger than the resolved photons distribution due to the coupling parameter ( $\alpha\alpha_s$ ) depresses the contribution of photon-partons. Therefore the yield of the resolved photon-plasma reaction partly modify the jet-plasma yield. The contribution of the resolved photon-dilepton conversion is almost 26% of the sum for the jet-plasma and  $\gamma(\text{resolved } \gamma)$ -plasma contribution from 0.5GeV-2.0GeV. The contribution of the real photon-plasma is contained in the  $K$  factor of jet-plasma processes. In Ref [28] the authors derived the jet-dilepton spectrum which is parallel to the Drell-Yan yield at the RHIC energy. In this Letter the jet-dilepton spectrum is depressed quickly with the increase of  $M^2$  due to the attenuation thermal function  $e^{-M^2/4P_T T}$  in equation (1).

From Fig. 2 one can see that the spectrum of dileptons is enhanced by the jet/ $\gamma(\text{resolved } \gamma)$ -plasma interaction mechanism (dash line) in the intermediate mass region between 1.0 GeV to 2.8 GeV compared to the traditional spectrum. The dot line means the contribution of the traditional thermal yield and Drell-Yan processes, and the expectation from the meson vacuum decays(v. d.). The numerical results match to the PHENIX data accurately at intermediate mass. The enhancement at low mass is not considered in this Letter, and the jet/ $\gamma(\text{res.}\gamma)$ -plasma interaction is just a weak contribution at low mass.

As a conclusion, we rigorously derive the yield of dileptons for the large  $P_T$  jet-plasma and  $\gamma(\text{resolved } \gamma)$ -plasma interaction mechanism. We find that the contribution of the jet-plasma and  $\gamma(\text{resolved } \gamma)$ -plasma dileptons is pronounced at intermediate mass, this mechanism satisfy the PHENIX data at intermediate mass.

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